

Oceanic Situational Awareness Over the Western Atlantic Track Routing System

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Abstract

Air traffic control (ATC) mandated, aircraft separations over the oceans impose a limitation on traffic capacity for a given corridor, given the projected traffic growth over the Western Atlantic Track Routing System (WATRS). The separations result from a lack of acceptable situational awareness over oceans where radar position updates are not available. This study considers the use of Automatic Dependent Surveillance (ADS) data transmitted over a commercial satellite communications system as an approach to provide ATC with the needed situational awareness and thusly allow for reduced aircraft separations. This study uses Federal Aviation Administration data from a single day for the WATRS corridor to analyze traffic loading to be used as a benchmark against which to compare several approaches for coordinating data transmissions from the aircraft to the satellites.

Introduction

Current procedures mandate that the Western Atlantic Track Routing System (WATRS) air traffic maintain 50 Nautical Mile (NMI) separations [1]. On the other hand, over Continental United States (CONUS) regions, Federal Aviation Administration (FAA) requires a 5 NMI separation. The difference in separation requirements is a direct result of the lack of surveillance radar coverage. Regularly derived position information from radar allows Air Traffic Control (ATC) to regularly monitor aircraft positions and react quickly to any changes. The very lack of surveillance radar over oceanic regions means that ATC does not have current position information, and therefore, must maintain much stricter separation requirements.

In the CONUS case where radar coverage is nearly ubiquitous, ATC radar data is automatically received at the regional control centers. Aircraft have little, if any, requirement to communicate nominal position information to ATC. Over the oceans, ATC must use High Frequency (HF) radio links to request position updates from each aircraft. HF radio has limitations in clarity and reliability. Additionally, HF communications are conducted through a third party. Direct controller-pilot communications are not possible which adds a time delay. HF radio does not mitigate the burden on ATC to obtain current position knowledge and therefore, the separation requirements cannot be relaxed.

This study explores the technical aspects of a satellite-based approach to oceanic aircraft surveillance that would provide ATC with more timely and reliable position information. This then may provide the means for reducing the current separation requirements and increasing oceanic corridor capacity. Specifically, by all aircraft in the WATRS corridor having their Automatic Dependant Surveillance (ADS) data transmitted to an Aeronautical Mobile Satellite System (AMSS) and the AMSS relaying that data to ATC, the required surveillance information would be available to support reduced separations. The potential AMSS that is considered in this study is a Low-Earth Orbiting (LEO) satellite system, but another AMSS in geostationary can fulfill the role as well. The reason for choosing one particular AMSS is that it provides needed communication systems data for both the space and air segments.

The goal of this study was to gain insight of the improvements possible by relaxing separation constraints. The study, however, did not address the numerous, strict procedures imposed on oceanic crossing aircraft. These aspects are left for future considerations.

Preliminary Considerations/Calculations

LEO Satellite Link

As an example of a LEO satellite system, the Iridium system operates in the L-Band frequency and the link examined uses the Sensor Systems Inc. aircraft mounted antenna, S65-8282-401 [2]. The antenna has a minimum elevation angle of 8° with a gain of 0 dBic. The antenna radiates 60 Watts (W) peak power which corresponds to an average power of 42.43 W. This specific antenna was modeled because it is representative of Iridium aircraft mounted antennas. Other link budget assumptions for the study are as follows:

- 3dB of Additional Losses
- QPSK Modulation [3]
- $1\text{E-}9$ BER
- Zenith Distance of 780 km [3]
- Horizon Distance of 2460 km [3]
- Frequency of 1.623 GHz
- Iridium Satellite G/T of -16.315 dB/K
- Burst Data Rate of 50 kbps [3]

The resulting link margins, table 1, for this case are shown below for both the zenith and horizon distances in order to scope the link margin extremes. The horizon distance represents the worst case scenario when the satellite is at an elevation angle of 8° , at the edge of the satellite footprint in the outermost spot beam cells.

TABLE 1.—LINK MARGIN RESULTS

Scenario	Zenith	Horizon
Margin (dB)	11.52	1.55

As shown in table 1, sufficient margin exists to complete a link, assuming level flight, for the antenna above 8° elevation angle.

Peak Traffic Baseline

According to the FAA data, November 26, 2003 was the heaviest traffic day in the WATRS corridor that year. Figure 1 shows that the maximum number of aircraft in the region at any time was 44. It is noted that the graph is multi-modal corresponding to the various surges within the various routes within the WATRS corridor.

The peak of 44 aircraft shown in figure 1 occurs at 21:13 GMT. Figure 2 depicts the aircraft position distribution throughout the WATRS corridor at that specified time. Note that the boundary for the WATRS corridor is depicted in red.

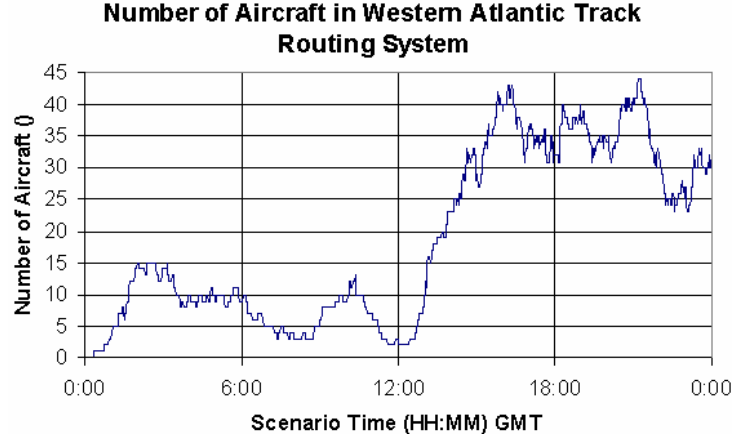


Figure 1.—Number of Aircraft in WATRS corridor.

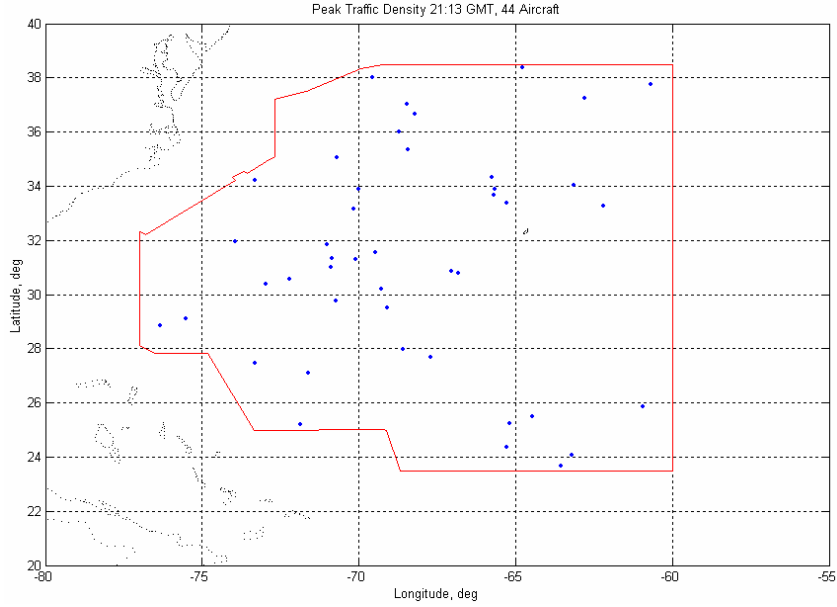


Figure 2.—Aircraft Coordinates at 21:13 GMT.

Corridor Capacity

A set of assumptions was used to compute the geometrical maximum number of aircraft in the corridor, C_G . C_G is computed in equation (1), based on the boundaries for the various routes (listed in table 2 and illustrated in fig. 3) and the aircraft separations.

$$C_G(A_{SEP}) = \sum_{i=1}^{19} \left[\left(\left\lceil \left[\frac{Alt_{MAX} - Alt_{MIN}}{Alt_{SEP}} \right] + 1 \right\rceil * \left(\left\lceil \left[\frac{MIN(d_{Ei}, d_{Wi})}{A_{SEP}} \right] + 1 \right\rceil * \left(\left\lceil \left[\frac{MIN(d_{Ni}, d_{Si})}{A_{SEP}} \right] + 1 \right\rceil \right) \right) \right] \quad (1)$$

where:

- A_{SEP} = aircraft separation distance (Nmi)
- Alt_{MAX} = corridor upper altitude = 40,000 ft
- Alt_{MIN} = corridor lower altitude = 37,000 ft
- Alt_{SEP} = required altitude separation = 1000 ft

- d_{Wi} = distance of western edge of route(i) (NMi) between
 - North-West boundary
 - South-West boundary
- d_{Ei} = distance of eastern edge of route(i) (NMi) between
 - North-East boundary
 - South-East boundary
- d_{Ni} = distance of northern edge of route(i) (NMi) between
 - North-West boundary
 - North-East boundary
- d_{Si} = distance of southern edge of route(i) (NMi) between
 - South-West boundary
 - South-East boundary

TABLE 2.—ROUTE BOUNDARIES

Route	North/West Boundary	South/East Boundary
1	(23.50°N,-63.50°E)	(27.00°N,-60.00°E)
2	(23.50°N,-66.30°E)	(29.40°N,-60.00°E)
3	(24.00°N,-68.65°E)	(31.80°N,-60.00°E)
4	(25.90°N,-73.75°E)	(32.80°N,-60.00°E)
5	(26.90°N,-74.30°E)	(34.50°N,-60.00°E)
6	(28.46°N,-77.00°E)	(35.20°N,-60.00°E)
7	(27.84°N,-75.90°E)	(38.50°N,-64.50°E)
8	(28.46°N,-77.00°E)	(38.50°N,-65.60°E)
9	(32.20°N,-77.00°E)	(32.37°N,-64.56°E)
10	(34.90°N,-72.70°E)	(37.50°N,-60.00°E)
11	(34.30°N,-73.80°E)	(25.00°N,-71.83°E)
12	(34.90°N,-72.70°E)	(25.00°N,-71.83°E)
13	(37.50°N,-71.70°E)	(25.00°N,-70.05°E)
14	(37.80°N,-71.15°E)	(23.50°N,-67.50°E)
15	(37.80°N,-71.15°E)	(23.50°N,-65.75°E)
16	(38.00°N,-70.60°E)	(34.00°N,-67.70°E)
17	(38.00°N,-70.60°E)	(23.50°N,-63.50°E)
18	(38.50°N,-68.00°E)	(32.37°N,-64.56°E)
19	(38.50°N,-66.60°E)	(23.50°N,-65.75°E)

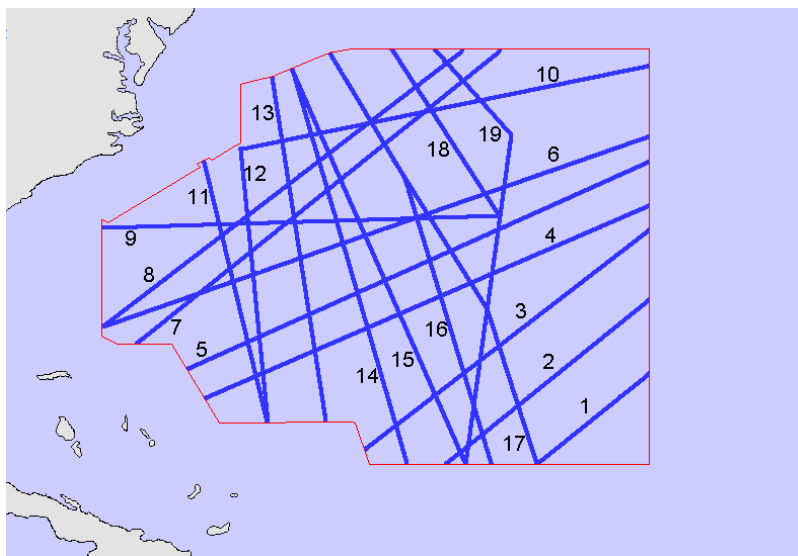


Figure 3.—WATRS Route Structure.

Figure 4 plots the maximum corridor geometric capacity, C_G , for aircraft separations between 1 and 50 NMi, for the WATRS corridor. Table 3 lists the maximum number of aircraft based on separations of 50, 30, and 15 NMi. Notice that by reducing the separation by a factor of 2 (30 NMi to 15 NMi), the corridor capacity nearly doubles (as there are no laterally separated aircraft on individual routes).

Based just on geometric considerations, even the currently mandated 50 NMi separation can accommodate more traffic than the peak traffic density of 44 aircraft. The value of 44 aircraft represents the peak instantaneous load for the busiest one-day traffic period in 2003 for the WATRS corridor.

TABLE 3.—MAXIMUM GEOMETRICAL CORRIDOR CAPACITY

Separation	WATRS
50 NMi Separation	1108
30 NMi Separation	1812
15 NMi Separation	3588

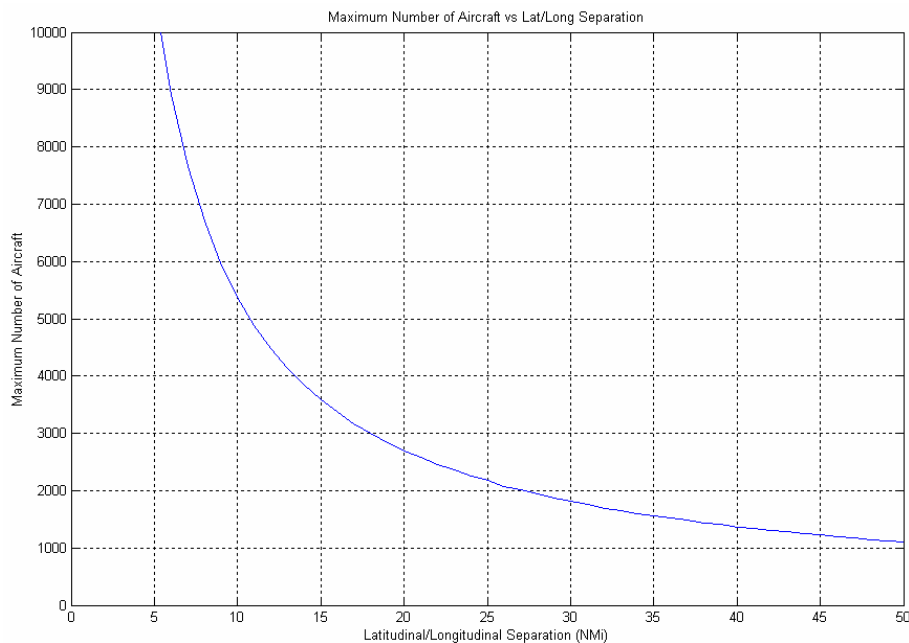


Figure 4.—Maximum Geometrical Corridor Capacity.

System Refresh Period

The maximum system refresh period is the upper limit of the amount of time between position information transmissions to ATC. The term “system refresh period” refers to the amount of time that is required for all of the aircraft in the corridor to transmit their messages one time. For aircraft separation reductions to occur safely, all aircraft in the corridor must transmit their position information within the maximum system refresh period for the reduced separations. System refresh period has components in lateral and longitudinal separation. System refresh period depends on the following [3] [4] [5]:

- Aircraft separation
- Required Navigation Performance (RNP) to aircraft separation ratio
- Latency (delay from transmission on aircraft to reception at ATC to warning message from ATC transmission to reception and pilot and aircraft response delay from warning message reception)
- Average aircraft speed
- Speed differential between aircraft
- Standard deviation for Global Positioning System (GPS) reported position
- Bank angle in lateral direction
- Deviation angle in lateral direction
- Aircraft are not flying on the same path in opposite directions
- Aircraft will not arbitrarily change altitudes

Assuming that all the aircraft maintain constant altitude, only lateral and longitudinal deviations are an issue. However, the period in between message transmissions represents a time when actual position of planes is uncertain. Therefore, by insisting that the separations remain larger than the distance two aircraft can close on each other during one system refresh period, the possibility of aircraft getting too close to one another during that time is minimized.

Equation (2), modified from work in [4], calculates the maximum system refresh period under longitudinal separation requirements.

$$T_{MAX_LONG}(A_{SEP}) = \frac{A_{SEP} - 4RNP - 4\sigma_{GPS}}{|\Delta v_{Aircraft}|} - T_{Latency} - T_{MAX_LONG}(A_{SEP}) \quad (2)$$

The term on the right hand side of equation (2) of the system refresh period ($T_{MAX_LONG}(A_{SEP})$) corresponds to the difference in time due to consecutively situated aircraft transmitting their position reports at time increments of one system refresh period. Equation (2) is solved for the system refresh period in equation (3).

$$T_{MAX_LONG}(A_{SEP}) = \frac{1}{2} * \left(\frac{A_{SEP} - 4RNP - 4\sigma_{GPS}}{\Delta v_{Aircraft}} - T_{Latency} \right) \quad (3)$$

A_{SEP} represents the aircraft separation distance. This study considers A_{SEP} values of 50, 30, or 15 NMi. RNP is the allowable position error from the planned flight path. For purposes of study, an RNP to separation ratio is defined and assumed to have a linear relationship, specifically, $RNP = k * A_{SEP}$, where k is the ratio between RNP and A_{SEP} . The assumption on linearity allows predicting required RNP levels for various separations. Historical data [5] [6] suggest a value of $k = 1/5$. Two historical examples and the projected RNP values for the remaining two separations are shown in table 4.

TABLE 4.—PROJECTED RNP REQUIREMENTS

A_{SEP}	RNP	k
100 NMi Separation	20 NMi	1/5
50 NMi Separation	10 NMi	1/5
30 NMi Separation	6 NMi	1/5
15 NMi Separation	3 NMi	1/5

Other parameters in equation (3) are:

- $\sigma_{GPS} = 60$ meter standard deviation for GPS
- $\Delta v_{Aircraft} = \frac{10 \text{ knots}}{60 \text{ minutes} / \text{hr}} = \text{relative aircraft to aircraft speed differential in NMi/min [7]}$
- $T_{Latency} = 7$ minutes [7]

It should be noted that due to the value of the total latency, $T_{Latency}$, it is possible for the maximum system refresh period to become a negative value. Since this is not allowed, the acceptable range for the maximum system refresh period is all real numbers greater than zero. Figure 5 plots the maximum system refresh period for the longitudinal separation component. Table 5 shows the maximum system refresh period for the three separations of interest.

**TABLE 5.—MAXIMUM SYSTEM REFRESH PERIOD—
LONGITUDINAL SEPARATION**

Separation (NMi)	Max. System Refresh Period (min)
50 NMi Separation	26.1
30 NMi Separation	14.1
15 NMi Separation	5.1

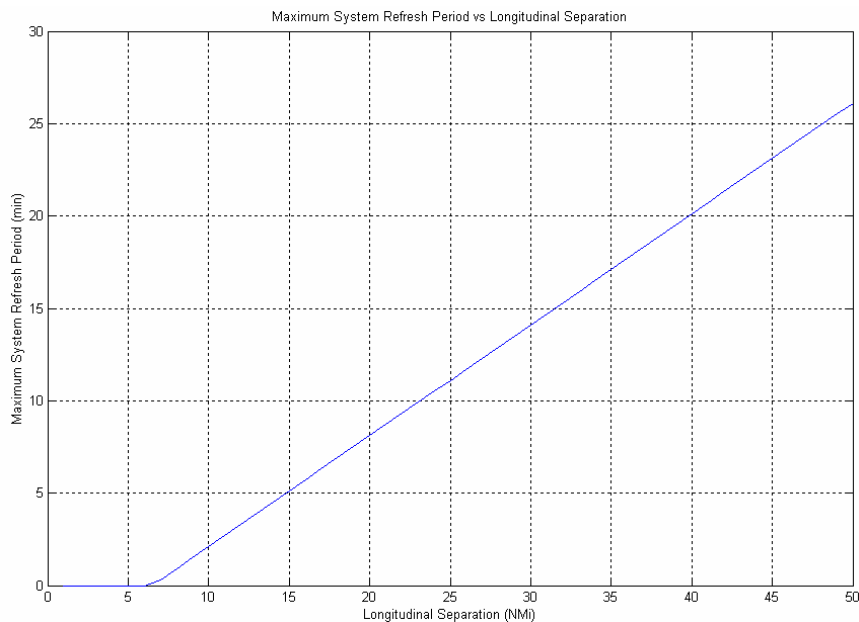


Figure 5.—Maximum System Refresh Period—Longitudinal Separation

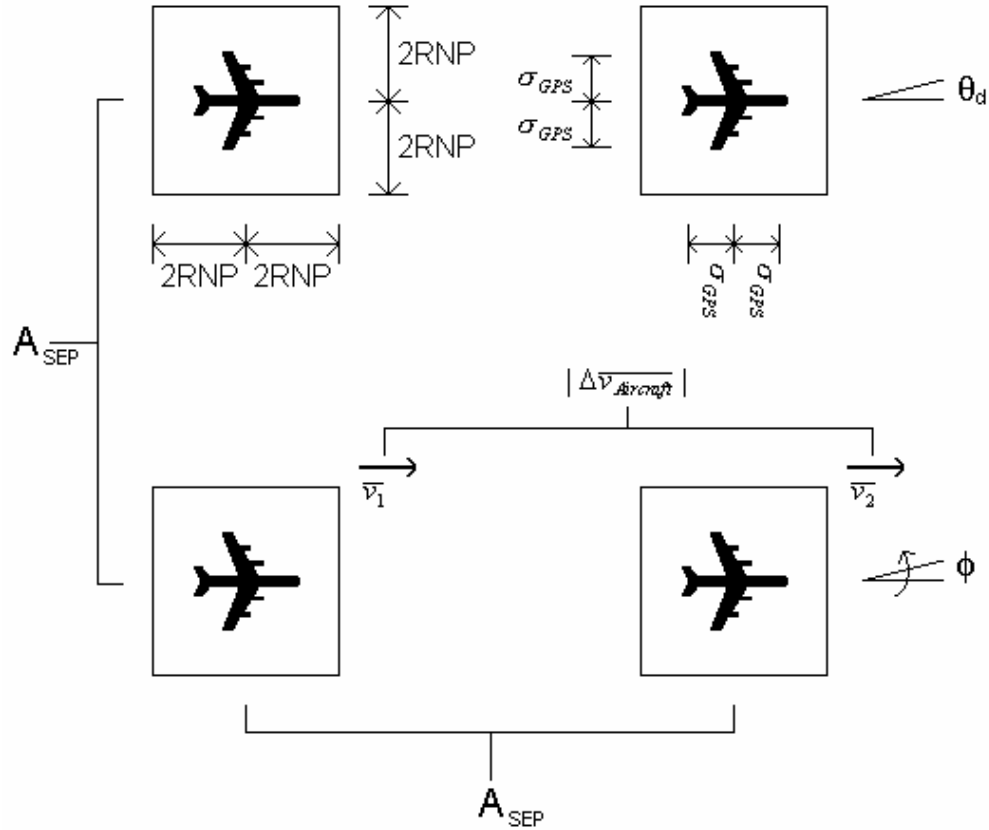


Figure 6.—Example of Aircraft Spacing

Figure 6 illustrates the physical spacing between aircraft that is assumed in equation (3) for longitudinal separation. In this figure, the box that surrounds each aircraft represents the containment region of the aircraft. This represents a box of area of 4RNP by 4RNP with the aircraft in the center. The aircraft will have a distance of 2RNP, i.e., 2σ deviation from planned flight path, to a box edge. A 2σ deviation means that the aircraft should remain on its pre-determined route 95% of the time. The standard deviation for the GPS coordinates of the aircraft, σ_{GPS} , also needs to be considered. The dimensions shown in this figure are not to scale but rather are notional. Also shown are the velocity vectors from which the speed deviation value is derived. Finally, the bank and deviation angles are illustrated, which will be utilized for lateral separation.

Equation (4), derived by International Civil Aviation Organization [8], calculates the maximum system refresh period under lateral separation requirements.

$$T_{MAX_LAT}(A_{SEP}) = \frac{60 \text{ min}}{hr} * \frac{A_{SEP} / 2 - 0.51 * RNP - \frac{V^2}{g * \tan(\phi)} (1 - \cos(\theta_d))}{V * \sin(\theta_d)} \quad (4)$$

Parameters in equation (4) that are not previously defined are:

- $V = 540$ knots average aircraft speed
- $g = 68584.32 \text{ NMi/hr}^2$ acceleration due to gravity
- $\phi = 15^\circ$ Bank angle for aircraft relative to nadir
- $\theta_d = 5.4^\circ$ Deviation angle for aircraft relative to trajectory

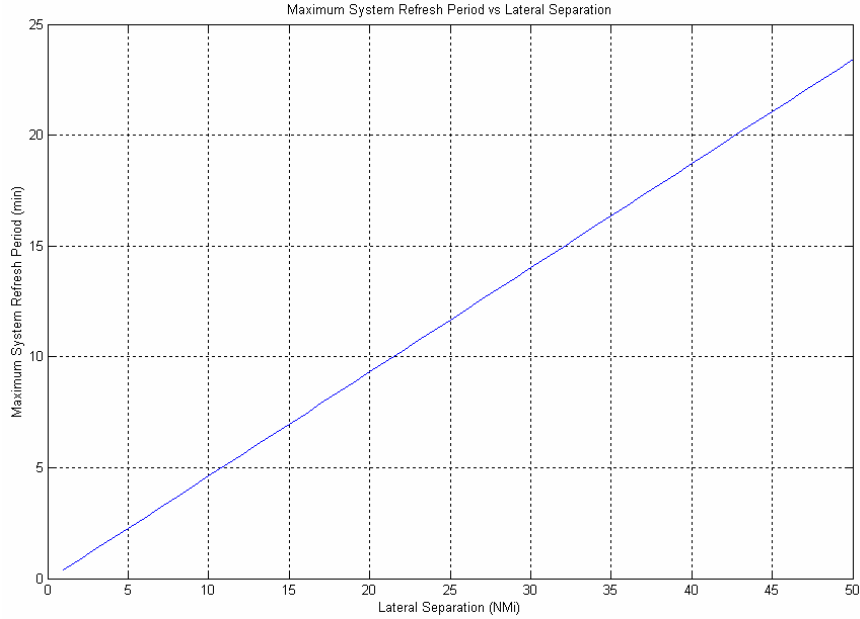


Figure 7.—Maximum System Refresh Period—Lateral Separation.

Figure 7 plots the maximum system refresh period for the lateral separation component. Table 6 shows the maximum system refresh period for the three separations of interest.

**TABLE 6.—MAXIMUM SYSTEM REFRESH PERIOD—
LATERAL SEPARATION**

Separation (NMi)	Max. System Refresh Period (min)
50 NMi Separation	23.4
30 NMi Separation	14.0
15 NMi Separation	7.0

Equation 5 shows the final equation used to compute the maximum system refresh period. It is the minimum of the maximum system refresh period for the longitudinal and lateral separations.

$$T_{MAX}(A_{SEP}) = MIN(T_{MAX_LONG}(A_{SEP}), T_{MAX_LAT}(A_{SEP})) \quad (5)$$

Figure 8 plots both the maximum system refresh period graphs together, with the longitudinal separation version in blue and the lateral separation version in red. Figure 9 plots the combined maximum system refresh period derived in equation (5). Table 7 shows the results for the three separations of interest.

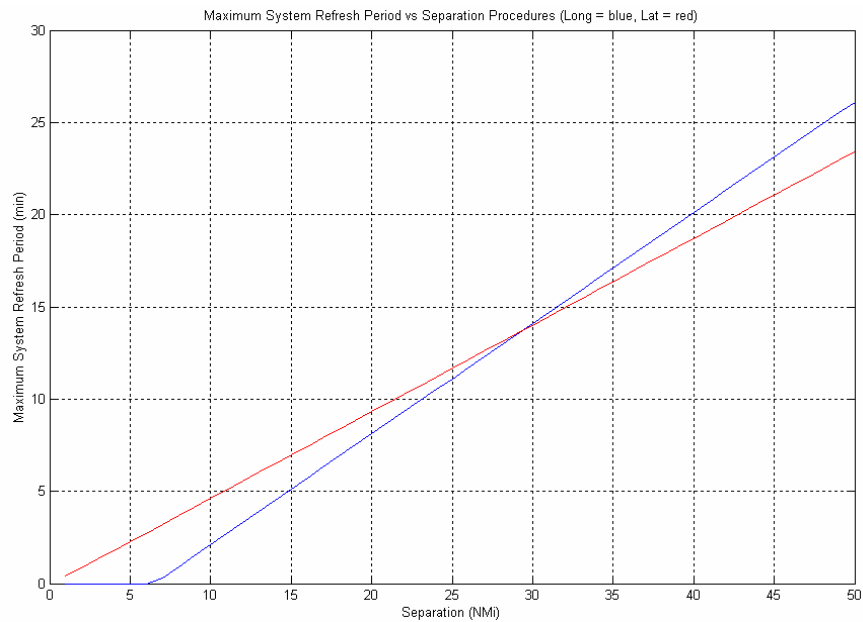


Figure 8.—Maximum System Refresh Period—Longitudinal and Lateral Separations.

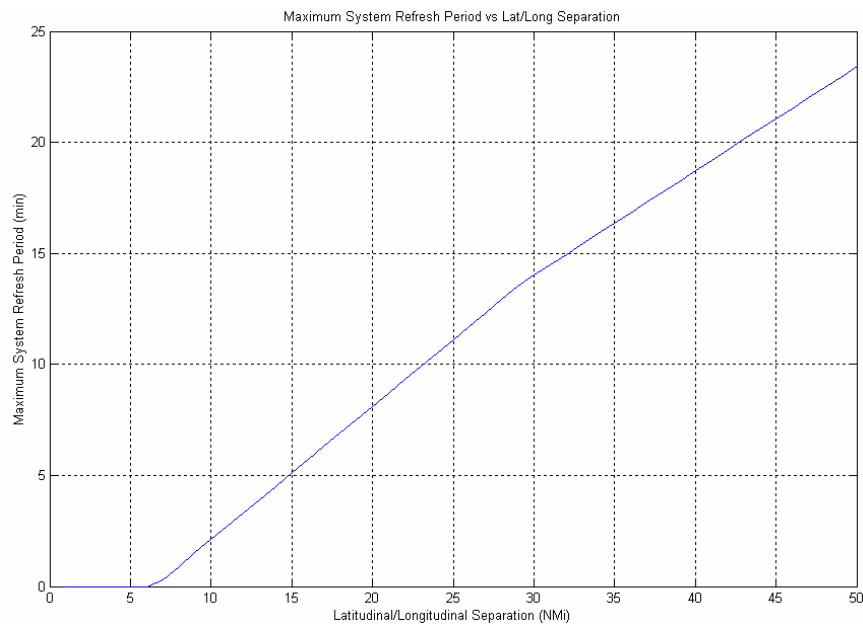


Figure 9.—Maximum System Refresh Period—Lateral/Longitudinal Separation.

**TABLE 7.—MAXIMUM SYSTEM REFRESH PERIOD—
LATERAL/LONGITUDINAL SEPARATION**

Separation (NMI)	Max. System Refresh Period (min)
50 NMI Separation	23.4
30 NMI Separation	14.0
15 NMI Separation	5.1

Transmission Methods

The following are two methods that were analyzed for the system of aircraft to transmit their GPS derived position for ADS messages. Each method consists of the message transmission description, a system refresh period for the peak traffic in each corridor, and the resulting maximum number of aircraft sustained in the corridor for the maximum system refresh period. The two methods are:

- Method 1—Single Aircraft Transmission at a Time
- Method 2—Maximum Aircraft Transmission at a Time

Each method will utilize some, if not most, of the following transmission scheme variables. These variables correspond to the Iridium system [3] [9] [10] and the ADS message format used for the analysis.

- T_{WAIT} = 0.33, 0.5, and 1 second inter-transmission waiting time between different aircraft transmissions
- T_{INIT} = 20 second initialization time to connect with Iridium (95% probability) [9]
- M_{CELL} = 48 spot beam cells per Iridium satellite (hereafter simply referred to as cell) [3]
- M_{FCH} = 20 frequency channels per Iridium cell [3]
- M_{TCHF} = 4 TDMA channels per frequency channel [3]
- $\%U_{CH}$ = 81.25% utilization of Iridium channels (not all Iridium channels are full duplex data compatible; therefore less than 100%) [10]
- R_D = System data rate of 2.4 kbps [3]
- T_{FRAME} = Iridium TDMA frame time of 90 milliseconds [3]
- No loss/re-establishment of link occurs during a transmission
- L_{ADS} = ADS message size of 80 bytes including coding [11]

Three values for the inter-transmission waiting time are used as this is an uncertain factor in the analysis. This is a parameter that was added to separate transmissions in time (and thus receptions at ATC). The lowest value of 0.33 seconds was determined to be such that initialization time was not a limiting factor in certain calculations. Given that the initialization process takes 20 seconds to complete (95% probability) and that 65 active communication channels exist within one cell, the minimum value for the inter-transmission waiting time is the initialization time over the number of active channels, which is just under 0.33 seconds. This means that if a delay of 0.33 seconds is added between transmissions between different aircraft, then up to 65 aircraft in a single cell can be in the process of initializing without conflict for initialization. The remaining values were chosen with the intention that they would help increase the probability for lack of conflict during initialization. There has been no risk analysis to determine what the probabilities would be with the two other inter-transmission waiting times.

ADS messages contain the full content of aircraft identification, latitude, longitude, altitude, time stamp, velocity, and future intent. The ADS message modeled is a generic message of size 80 bytes [11]. This message size includes additional coding to help aid in error prevention in the transmission process.

Method 1

In the single aircraft transmission at a time method, two possibilities were considered. In the first case, the single transmitting aircraft is sending only its own position information. In the second case, the single transmitting aircraft is sending its own plus some of its neighbors' position information.

Case 1.—In the first case of Method 1, a single aircraft will transmit its own position information, while others prepare to transmit theirs by initializing their transmitters with the LEO satellite system. An inter-transmission waiting time in the range of 0.33 seconds to one second must elapse before another aircraft in the corridor can transmit. After the completion of the first aircraft's transmission, one of the aircraft which has not transmitted during the current refresh period will initialize with the LEO satellite system. Aircraft will begin to initialize their transmitters 20 seconds prior to their scheduled transmission. The initialization time is not a factor in the calculations because while aircraft $n+1$ up to aircraft $n+65$ (for 0.33 second inter-transmission waiting time; $n+40$ for 0.5 second inter-transmission waiting time; $n+20$ for 1 second inter-transmission waiting time) are initializing, aircraft n is transmitting so initialization does not contribute a delay to actual operations. This process will continue until all aircraft in the corridor transmit their position information during each system refresh period.

Figure 10 shows an example diagram for Case 1. Note that each aircraft in the corridor has its unique transmission time assignment, represented by $\{T1, T2, T3, \dots\}$. These time assignments do not reflect the frequency or time slot that is assigned for the transmission during initialization. It is assumed in the diagram that there are zero conflicts for frequency and time slot assignment.

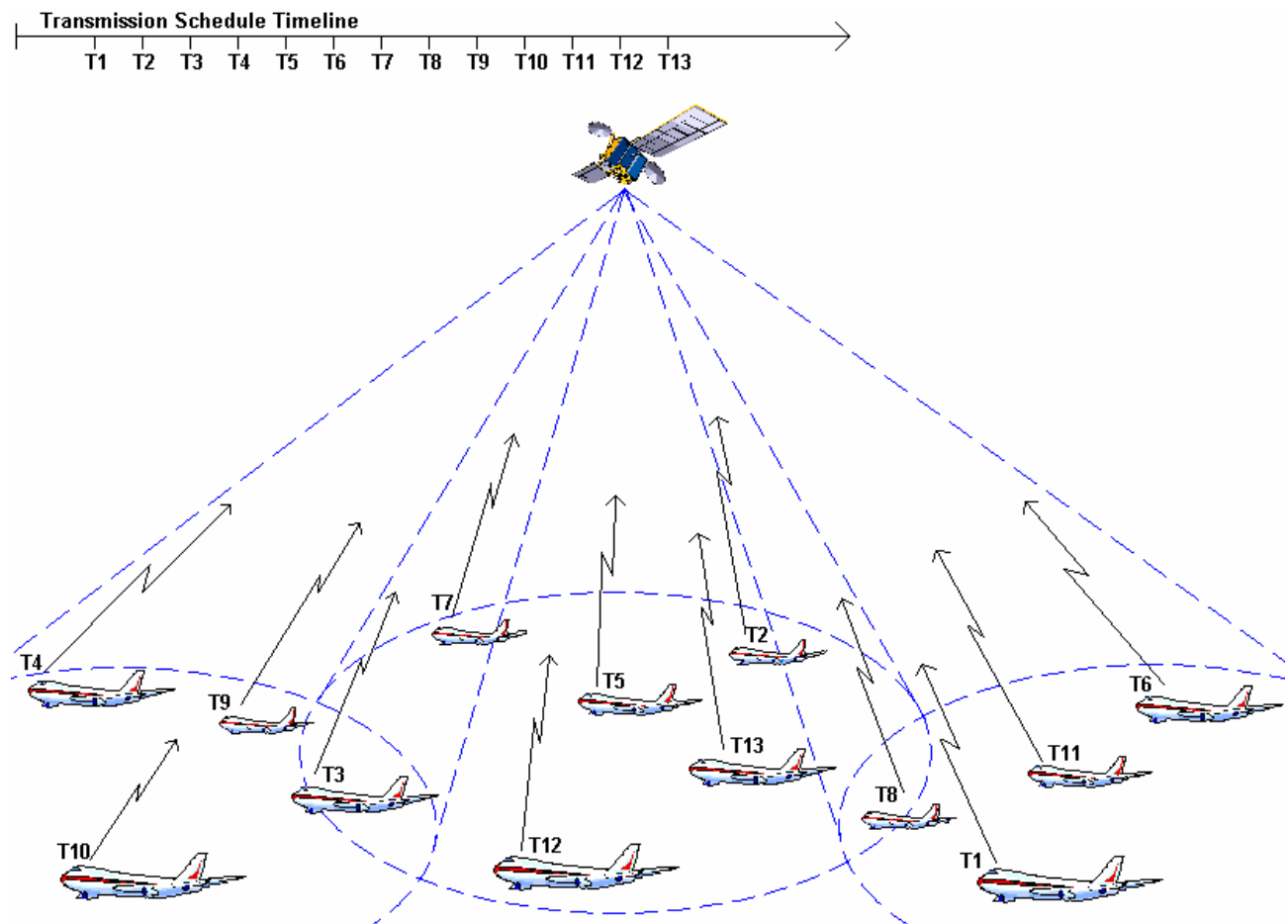


Figure 10.—Example Diagram for Method 1, Case 1.

Case 2.—In the second case of Method 1, the transmitting aircraft has knowledge of the position information of neighboring aircraft as well as its own, and those aircraft have knowledge, by use of a status bit, that a particular aircraft will transmit their position information messages. Therefore, those surrounding aircraft will not attempt to initialize and transmit through the LEO satellite system. By insisting that the number of messages that each transmitting aircraft sends be the same, system refresh time can be reduced. The result is fewer transmitting aircraft, fewer messages sent over the LEO satellite system, and a reduction in recurring cost.

Figure 11 shows an example diagram for Case 2. Note that each transmitting aircraft in the corridor has its unique transmission time assignment, represented by $\{T1, T2, T3, \dots\}$. These time assignments do not reflect the frequency or time slot that is assigned for the transmission during initialization. It is assumed in the diagram that there are zero conflicts for frequency and time slot assignment. Also, note the transmission links between aircraft. This represents the sharing of position reports on a different link than the LEO satellite system link. The link for sharing these reports is of Automatic Dependent Surveillance – Broadcast (ADS-B).

The order for which the aircraft will transmit in Method 1 can be accomplished through coordination with ATC. At the time that aircraft are entering the corridor, they are still within HF range. Therefore, using HF communications, ATC can specify the ADS contracts for an initial transmission time to each aircraft as they enter the corridor, as well as the amount of time between transmissions (system refresh period). Since ATC would be monitoring the flow of traffic over the corridor, it would have knowledge of when aircraft are exiting the corridor, so transmission slots can be reassigned to new aircraft entering the corridor.

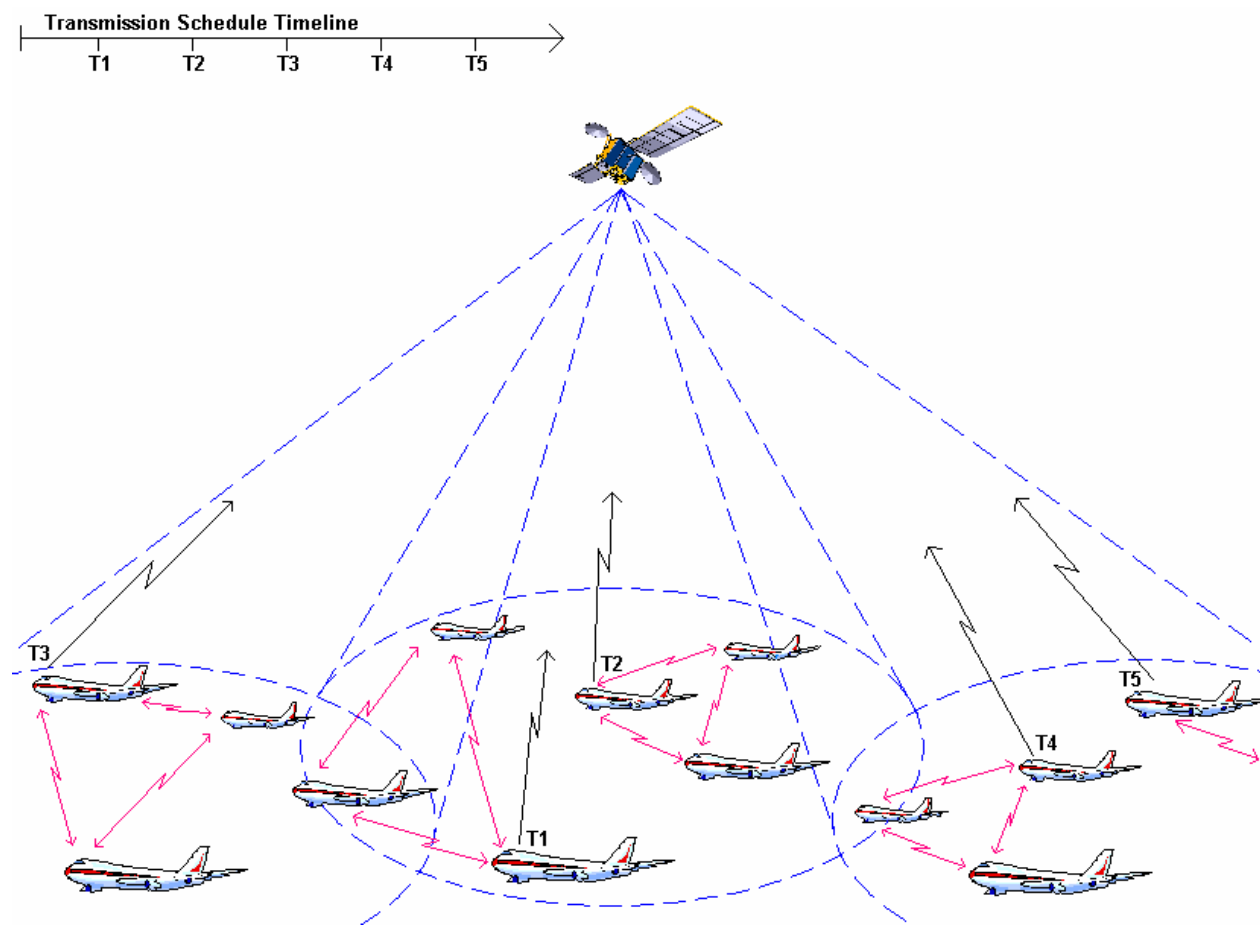


Figure 11.—Example Diagram for Method 1, Case 2.

The required system refresh period for Method 1 is the minimum system refresh period that N number of aircraft will require to transmit their position information to ATC once. This minimum system refresh period, $(T_{MIN1}(N,b))$, is a function of the number of aircraft in the corridor (N) and the number of messages per transmission (b). Equation 6 computes the minimum system refresh period.

$$T_{MIN1}(N,b) = \left(\frac{T_{FRAME} * \left[\frac{b * 8 * L_{ADS}}{R_D * T_{FRAME}} \right] + T_{WAIT}}{60 \text{ sec/min}} \right) * \left(\left\lceil \frac{N}{b} \right\rceil \right) \quad (6)$$

where:

- N = number of aircraft in the corridor
- b = number of messages per transmission
- L_{ADS} = length of ADS message of 80 bytes
- T_{FRAME} = Iridium TDMA frame time of 0.090 seconds
- R_D = System data rate of 2.4 kbps
- T_{WAIT} = 0.33, 0.5, and 1 second inter-transmission waiting times between different aircraft transmissions

Table 8 shows the minimum system refresh period for the peak traffic load of 44 aircraft for the WATRS corridor over the three inter-transmission waiting times. Note that one message per transmission is the first case ($b = 1$); a single aircraft transmitting its own position information. Two or more messages per transmission are the second case ($b > 1$) where one aircraft is transmitting position information for itself plus as many as 11 other aircraft in its ADS vicinity.

TABLE 8.—REQUIRED SYSTEM REFRESH PERIOD (MINUTES)

Messages per Transmission	Inter-Transmission Waiting Time		
	0.33 sec	0.5 sec	1.0 sec
1	0.44	0.56	0.93
2	0.32	0.38	0.56
4	0.26	0.29	0.38
12	0.24	0.25	0.28

For Method 1, the maximum number of possible aircraft in the corridor can be computed based on the geometrical limit in the corridor, LEO satellite data rate, waiting time between aircraft transmissions, and the combined message lengths for the ADS messages. This can be computed by solving equation (6) for the maximum number of aircraft that can be accommodated by the communication scheme, by substituting the maximum system refresh period ($T_{MAX}(A_{SEP})$) for the minimum system refresh period ($T_{MIN1}(N,b)$). Equation (7) computes the capacity for the communication scheme for Method 1 ($C_{C1}(A_{SEP},b)$).

$$C_{C1}(A_{SEP},b) = b * \left\lceil \frac{T_{MAX}(A_{SEP}) * 60 \text{ sec/min}}{\left(T_{FRAME} * \left[\frac{b * 8 * L_{ADS}}{R_D * T_{FRAME}} \right] + T_{WAIT} \right)} \right\rceil \quad (7)$$

where:

- b = number of messages per transmission
- $T_{MAX}(A_{SEP})$ = maximum system refresh period dependent on A_{SEP} (separation)
- L_{ADS} = length of ADS message of 80 bytes
- T_{FRAME} = Iridium TDMA frame time of 0.090 seconds
- R_D = System data rate of 2.4 kbps
- T_{WAIT} = 0.33, 0.5, and 1 second inter-transmission waiting times between different aircraft transmissions

Figure 12 shows the maximum number of aircraft as a function of separation for the 0.33 second inter-transmission waiting time. Note that for each case of b , the number of messages per transmission, the resulting graph is a straight line that associates number of aircraft that can be supported at a given separation with the specified maximum system refresh period for that given separation.

As separation increases, for a given value of b , the system refresh period also increases. The reason is, as aircraft are further apart, there is a less frequent need for position updates to maintain good separation knowledge (see fig. 9). Figure 12 shows that for a given value of b , as separation increases, the maximum number of aircraft also increases. As just stated, separation increases relate directly to increases in maximum system refresh period. In turn, increasing maximum system refresh period will directly increase the number of messages that can be sent. Finally, the number of aircraft that can be supported will increase, by a factor of b , as the number of messages sent increases. Intuitively, as the number of messages per transmission increases, then the time required for a single transmission will increase, which will decrease the number of possible transmission sent during a given time interval. However, as the number of possible transmissions sent will decrease, the overall number of aircraft that the system can handle will increase due to the larger number of aircraft position reports being sent per transmission.

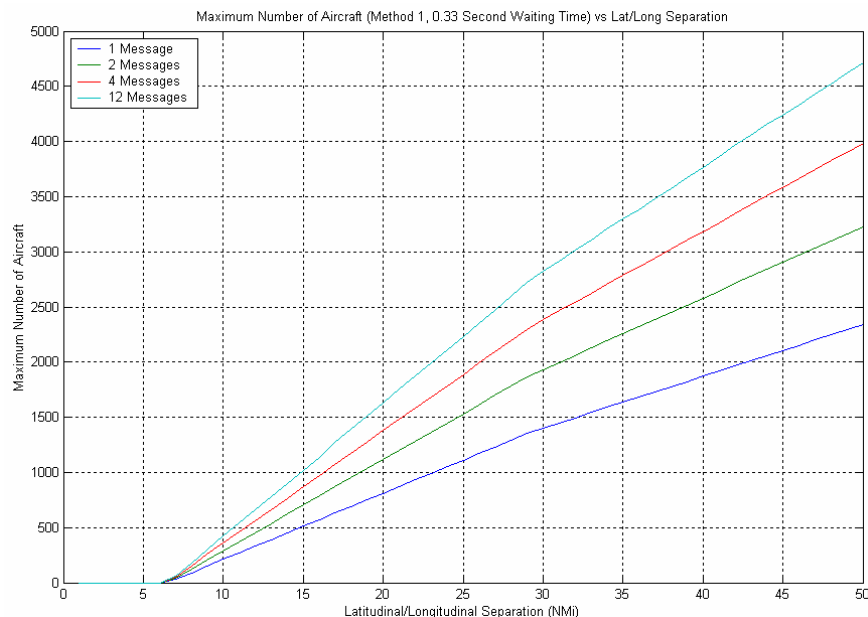


Figure 12.—Maximum Number of Aircraft—0.33 Second Inter-Transmission Waiting Time.

Equation (8) computes the overall maximum number of aircraft in the corridor as the lower bound between the geometrical capacity and the communication scheme capacity at varying separations.

$$C_1(A_{SEP}, b) = \text{MIN}(C_G(A_{SEP}), C_{C1}(A_{SEP}, b)) \quad (8)$$

Given the maximum system refresh period, the maximum number of aircraft that the corridor can sustain for Method 1 is computed for the three inter-transmission waiting times. The results are plotted in figures 13 through 15 for inter-transmission waiting times of 0.33, 0.5, and 1.0 seconds, respectively.

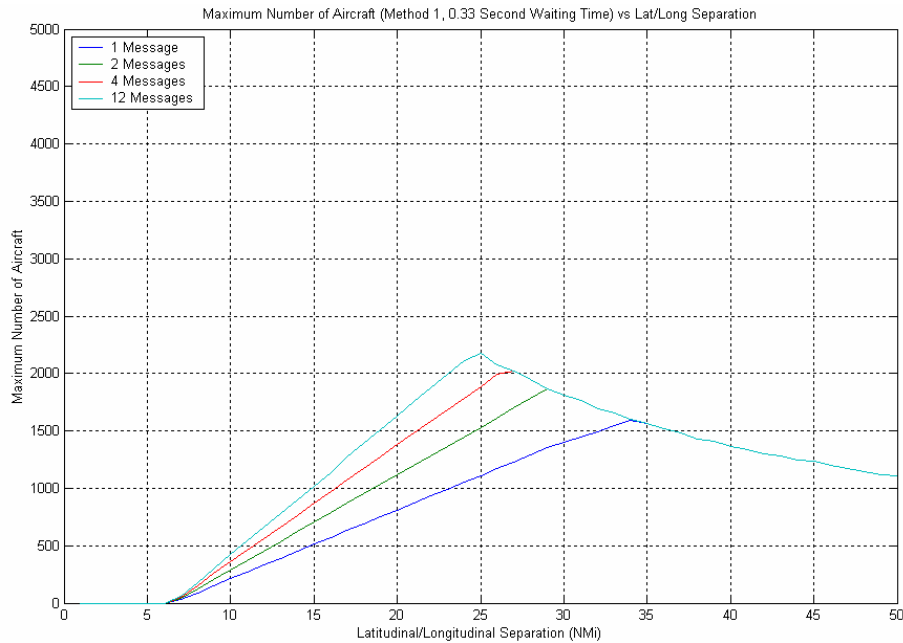


Figure 13.—Maximum Number of Aircraft—0.33 Second Inter-Transmission Waiting Time.

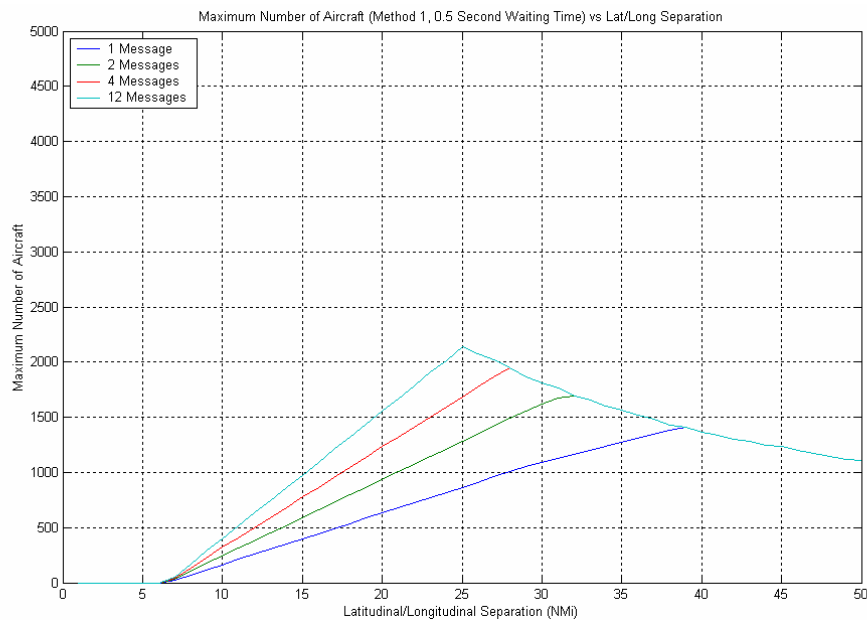


Figure 14.—Maximum Number of Aircraft—0.5 Second Inter-Transmission Waiting Time.

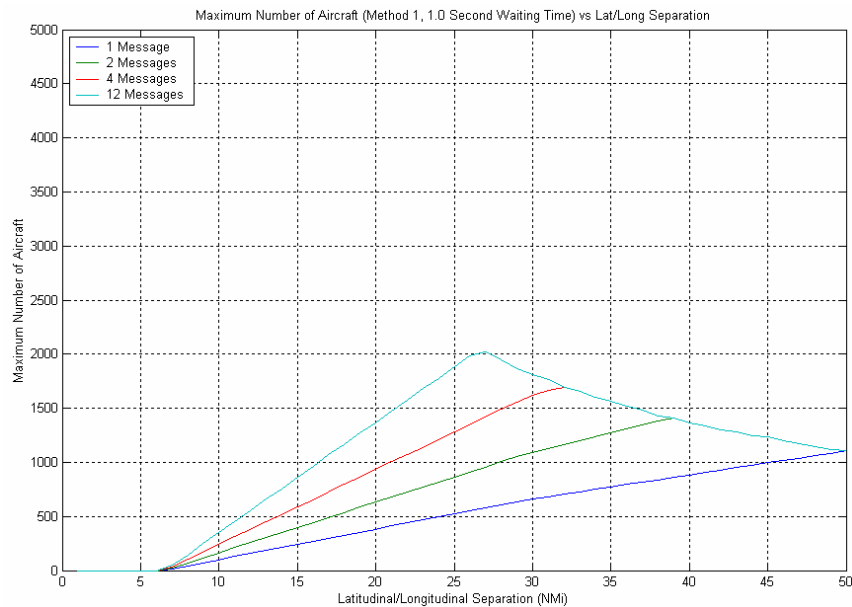


Figure 15.—Maximum Number of Aircraft—1.0 Second Inter-Transmission Waiting Time.

Figures 13 through 15 show the combined effects of geometric and communications systems limits for the WATRS corridor. The right hand boundaries observed in figures 13 through 15 represent the geometric limits for maximum possible number of aircraft, as a function of aircraft separation (see fig. 4), while the straight lines represent communications limits based on maximum system refresh period, as a function of aircraft separation (see fig. 12).

Table 9 lists the results for the three lateral/longitudinal separations versus the number of messages per transmission versus the inter-transmission waiting time for the WATRS corridor. Note that Method 1 can easily accommodate the current peak density of traffic in all cases.

TABLE 9.—MAXIMUM NUMBER OF AIRCRAFT—METHOD 1

Messages per Transmission	50 NMi			30 NMi			15 NMi		
	0.33 sec	0.5 sec	1.0 sec	0.33 sec	0.5 sec	1.0 sec	0.33 sec	0.5 sec	1.0 sec
1	1108	1108	1106	1401	1092	662	511	398	241
2	1108	1108	1108	1812	1616	1092	704	588	398
4	1108	1108	1108	1812	1812	1616	868	776	588
12	1108	1108	1108	1812	1812	1812	1020	972	864

From these three inter-transmission waiting times, the best results in terms of maximum number of aircraft in the region occur when the inter-transmission waiting time is 0.33 seconds. This is because the 0.33 second inter-transmission waiting time results in less time between transmissions which allows more aircraft to transmit in a given system refresh period. The largest maximum corridor capacity occurs over the 30 NMi separation at 1812 aircraft at 0.33 or 0.50 second inter-transmission waiting time with 4 or 12 messages per transmission.

Method 2

In the maximum aircraft transmission at a time method, two possibilities were again considered. In the first case, transmitting aircraft send only their own position information. In the second case, the

maximum number of transmitting aircraft sends their own plus information of its neighbors' position information.

Case 1.—In the first case of Method 2, a maximum number of aircraft in the corridor will transmit their position information. This maximum number of concurrent transmissions is determined from the number of available LEO satellite data transmission channels in a cell. However, as the distribution of aircraft is dynamic over the moving LEO satellite cells, the maximum possible number of concurrent transmissions in the corridor is the maximum number of active data channels in a single cell. Once the first group of 65 aircraft transmits their position information, an inter-transmission waiting time separation is elapsed before another group of 65 aircraft begins to initialize and transmit to the LEO satellite system. In this method, the initialization time is a factor because group $n+1$ might be partially, or fully, covered within the same cell(s) as group n . This cycle will repeat as necessary for all the aircraft in the corridor to transmit their position information during each system refresh period.

Figure 16 shows an example diagram for Case 1. Note that each aircraft in the corridor has a transmission time assignment, represented by $\{T1, T2, T3, \}$. These time assignments do not reflect the frequency or time slot that is assigned for the transmission during initialization. It should be noted that several aircraft have the same transmission time assignment $\{T1, T2, \}$. For those with the same time assignment, transmissions will take place concurrently. It is assumed in the diagram that there are zero conflicts for frequency and time slot assignment. Thus, if two aircraft are in the same cell and have the same time assignment, then they will be on a different frequency or time slot from each other.

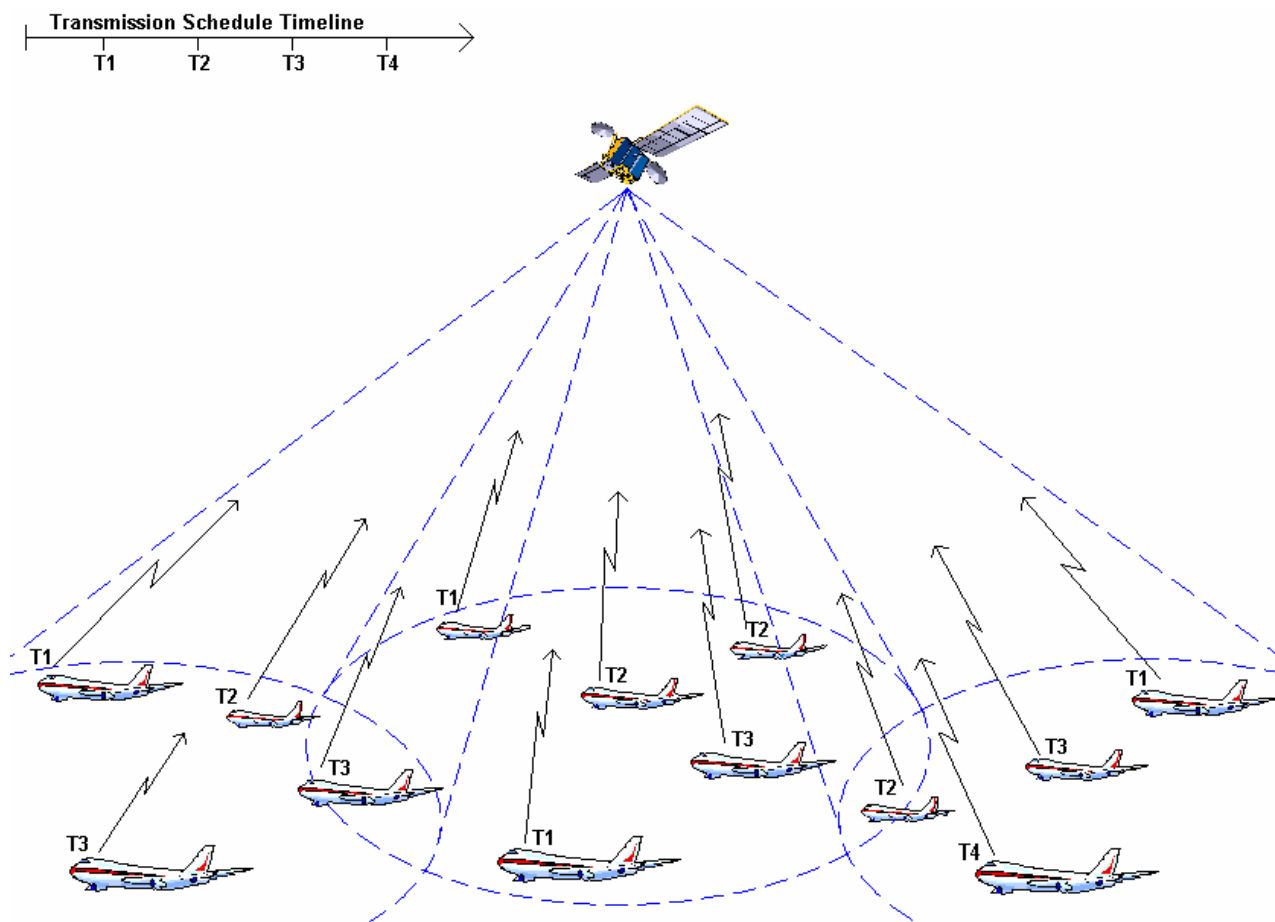


Figure 16.—Example Diagram for Method 2, Case 1.

Case 2.—In the second case of Method 2, the transmitting aircraft have knowledge of the position information of surrounding aircraft as well as their own, and those aircraft have knowledge that a set of aircraft will transmit their position information messages. Therefore, those surrounding aircraft will not attempt to initialize and transmit through the LEO satellite system. By insisting that the number of messages that each transmitting aircraft sends be the same, system refresh time can be reduced. The result is fewer transmitting aircraft, fewer messages sent over the LEO satellite system, and a reduction in recurring cost.

Figure 17 shows an example diagram for Case 2. Note that each transmitting aircraft in the corridor has a transmission time assignment, represented by $\{T1, T2, T3\}$. These time assignments do not reflect the frequency or time slot that is assigned for the transmission during initialization. Also, note the transmission links between aircraft. This represents the sharing of position reports on a different link than the LEO satellite system link. The link for sharing these reports is ADS-B. For those with the same time assignment, transmissions will take place concurrently. It is assumed in the diagram that there are zero conflicts for frequency and time slot assignment. Thus, if two aircraft are in the same cell and have the same time assignment, then they will be on a different frequency or time slot from each other.

The order for which the aircraft will transmit in Method 2 can be accomplished through coordination with ATC. At the time that aircraft are entering the corridor, they are still within HF range. Therefore, using HF communications, ATC can specify the ADS contracts for an initial transmission time to each aircraft as they enter the corridor, as well as the amount of time between transmissions (system refresh period). Since ATC would be monitoring the flow of traffic over the corridor, it would have knowledge of when aircraft are exiting the corridor, so it can open up those transmission slots for new aircraft upon entering the corridor.

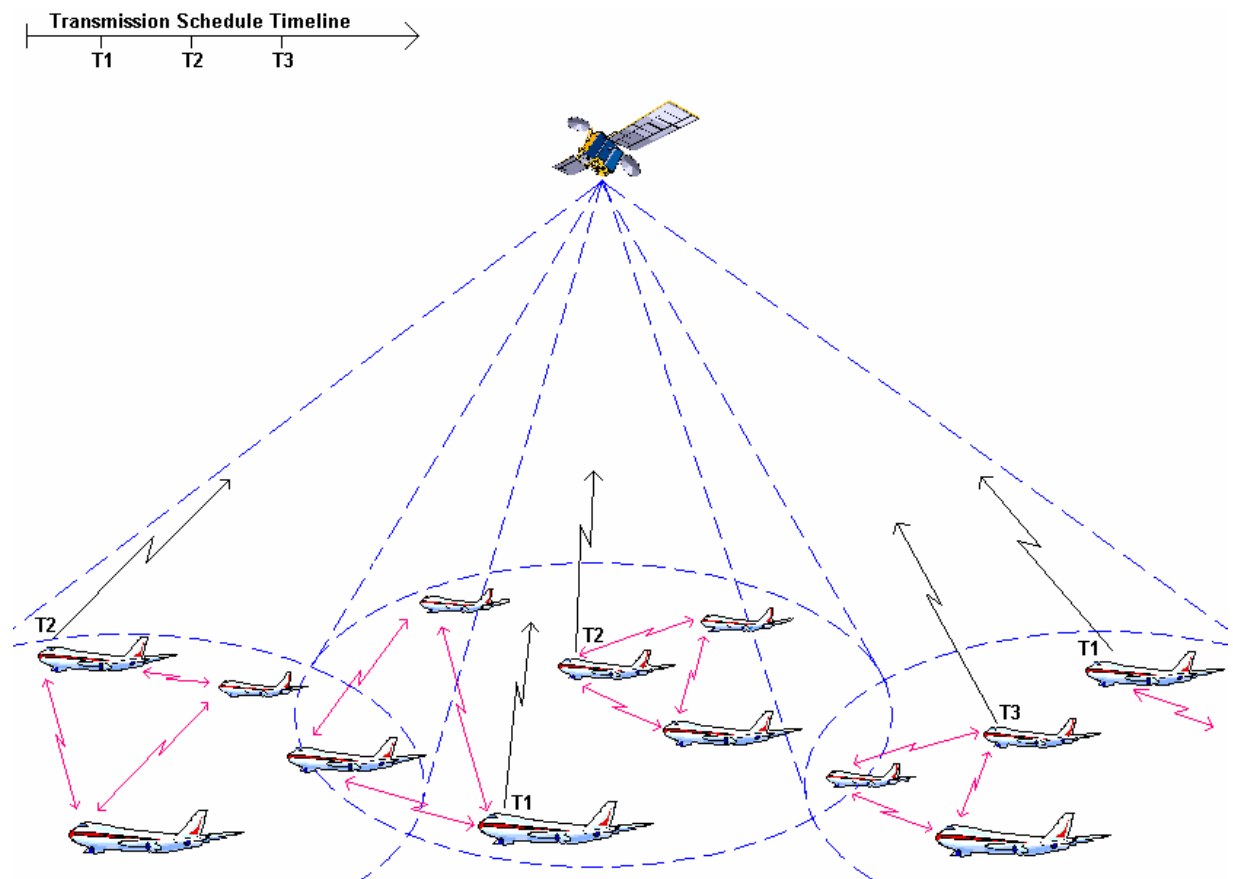


Figure 17.—Example Diagram for Method 2, Case 2.

The required system refresh period for Method 2 is the minimum system refresh period that N number of aircraft will require to transmit their position information to ATC once. This minimum system refresh period, $T_{MIN2}(N,b)$, is a function of the number of aircraft in the corridor (N) and the number of messages per transmission (b). Equation (9) computes the minimum system refresh period.

$$T_{MIN2}(N,b) = \left(\frac{T_{FRAME} * \left[\frac{b * 8 * L_{ADS}}{R_D * T_{FRAME}} \right] + T_{WAIT} + T_{INIT}}{(60 \text{ sec/min}) * [M_{FCH} * M_{TCHF} * \%U_{CH}]} \right) * \left(\left\lceil \frac{N}{b} \right\rceil \right) \quad (9)$$

where:

- N = number of aircraft in the corridor
- b = number of messages per transmission
- L_{ADS} = length of ADS message of 80 bytes
- T_{FRAME} = Iridium TDMA frame time of 0.090 seconds
- R_D = System data rate of 2.4 kbps
- T_{WAIT} = 0.33, 0.5, and 1 second inter-transmission waiting times between different aircraft transmissions
- T_{INIT} = 20 second initialization time to connect with Iridium (95% probability)
- M_{FCH} = 20 frequency channels per Iridium cell
- M_{TCHF} = 4 TDMA channels per frequency channel
- $\%U_{CH}$ = 81.25% utilization of Iridium channels (not all Iridium channels are full duplex data compatible; therefore less than 100%)

Table 10 shows the minimum system refresh period for the peak traffic load of 44 aircraft for the WATRS corridor over the three inter-transmission waiting times. Note that one message per transmission is the first case ($b = 1$); a single aircraft transmitting its own position information. Two or more messages per transmission are the second case ($b > 1$) where one aircraft is transmitting position information for itself plus as many as 11 other aircraft in its ADS vicinity.

TABLE 10.—REQUIRED SYSTEM REFRESH PERIOD (MINUTES)

Messages per Transmission	Inter-Transmission Waiting Time		
	0.33 sec	0.5 sec	1.0 sec
1	0.23	0.23	0.24
2	0.12	0.12	0.12
4	0.06	0.06	0.06
12	0.02	0.02	0.02

For Method 2, the maximum number of possible aircraft in the corridor can be computed based on the geometrical limit in the corridor, LEO satellite data rate, waiting time between messages, initialization time to the LEO satellite system, combined message lengths for the ADS messages, LEO satellite transmission channels per cell, and LEO satellite transmission channel utilization. This can be computed by solving equation (9) for the maximum number of aircraft that can be accommodated by the communication scheme, by substituting the maximum system refresh period ($T_{MAX}(A_{SEP})$) for the minimum system refresh period $T_{MIN2}(N,b)$. Equation (10) computes the capacity for the communication scheme for Method 2.

$$C_{C2}(A_{SEP}, b) = b * \left[\frac{T_{MAX}(A_{SEP}) * (60 \text{ sec/min}) * [M_{FCH} * M_{TCHF} * \%U_{CH}]}{\left(T_{FRAME} * \left[\frac{b * 8 * L_{ADS}}{R_D * T_{FRAME}} \right] + T_{WAIT} + T_{INIT} \right)} \right] \quad (10)$$

where:

- b = number of messages per transmission
- $T_{MAX}(A_{SEP})$ = maximum system refresh period dependent on A_{SEP} (separation)
- L_{ADS} = length of ADS message of 80 bytes
- T_{FRAME} = Iridium TDMA frame time of 0.090 seconds
- R_D = System data rate of 2.4 kbps
- T_{WAIT} = 0.33, 0.5, and 1 second inter-transmission waiting times between different aircraft transmissions
- T_{INIT} = 20 second initialization time to connect with Iridium (95% probability)
- M_{FCH} = 20 frequency channels per Iridium cell
- M_{TCHF} = 4 TDMA channels per frequency channel
- $\%U_{CH}$ = 81.25% utilization of Iridium channels (not all Iridium channels are full duplex data compatible; therefore less than 100%)

Equation (11) computes the overall maximum number of aircraft in the corridor as the lower bound between the geometrical capacity and the communication scheme capacity at varying separations.

$$C_2(A_{SEP}, b) = \text{MIN}(C_G(A_{SEP}), C_{C2}(A_{SEP}, b)) \quad (11)$$

Given the maximum system refresh period, the maximum number of aircraft that the corridor can sustain for Method 2 is computed for the three inter-transmission waiting times. The results are plotted in figures 18 through 20 for inter-transmission waiting times of 0.33, 0.5, and 1.0 seconds, respectively.

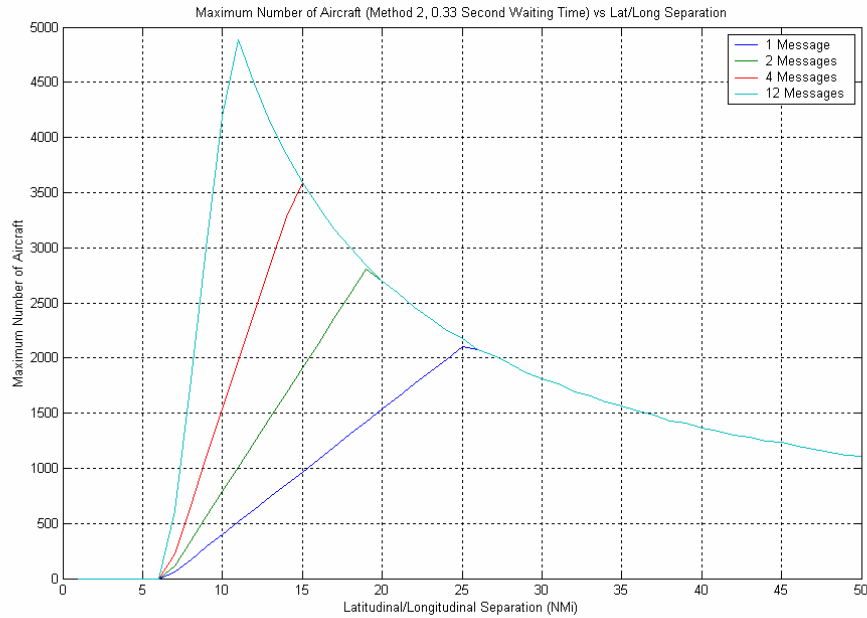


Figure 18.—Maximum Number of Aircraft—0.33 Second Inter-Transmission Waiting Time.

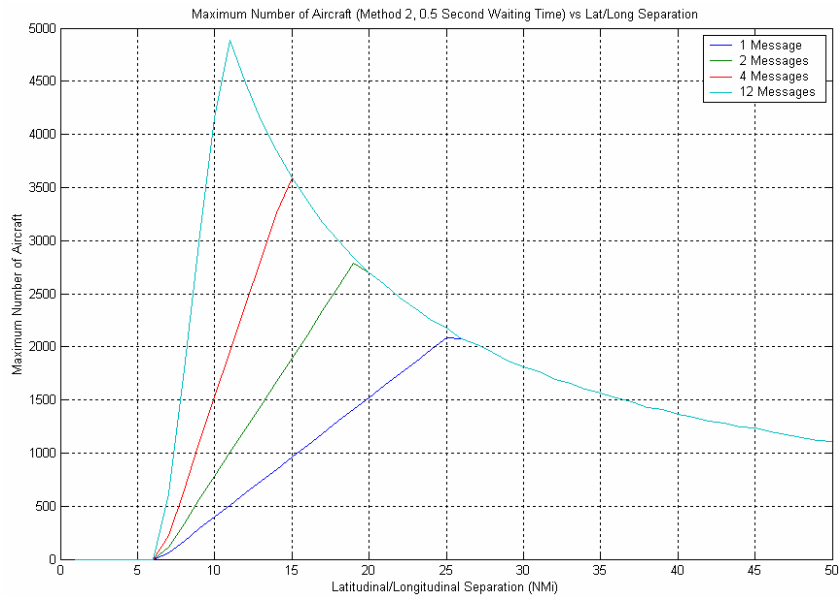


Figure 19.—Maximum Number of Aircraft—0.5 Second Inter-Transmission Waiting Time.

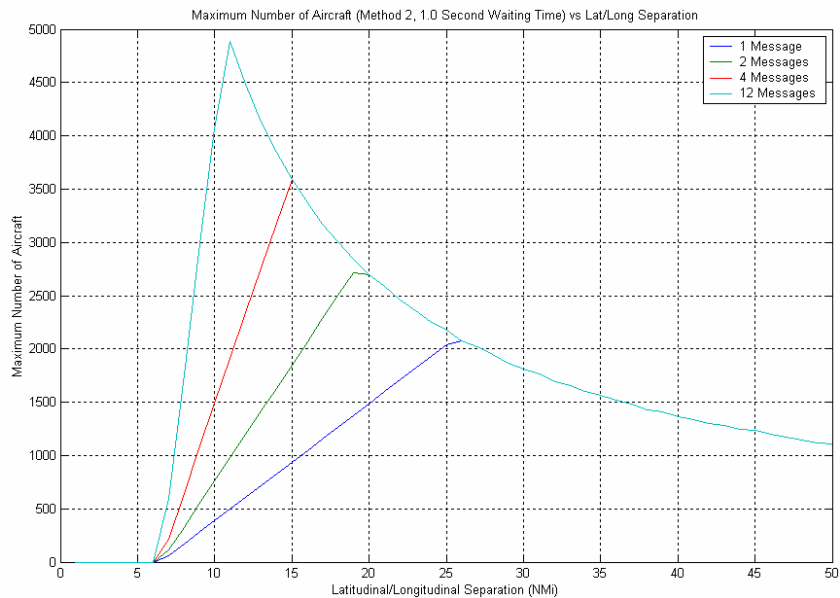


Figure 20.—Maximum Number of Aircraft—1.0 Second Inter-Transmission Waiting Time.

Figures 18 through 20 show the combined effects of geometric and communications systems limits for the WATRS corridor. The right hand boundaries observed in figures 18 through 20 represent the geometric limits for maximum possible number of aircraft, as a function of aircraft separation (see fig. 4), while the straight lines represent communications limits based on maximum system refresh period, as a function of aircraft separation (see fig. 12).

Table 11 lists the results for the three lateral/longitudinal separations versus the number of messages per transmission versus the inter-transmission waiting time for the WATRS corridor. Note that Method 2 can easily accommodate the current peak density of traffic in all cases.

TABLE 11.—MAXIMUM NUMBER OF AIRCRAFT—METHOD 2

Messages per Transmission	50 NMi			30 NMi			15 NMi		
	0.33 sec	0.5 sec	1.0 sec	0.33 sec	0.5 sec	1.0 sec	0.33 sec	0.5 sec	1.0 sec
1	1108	1108	1108	1812	1812	1812	967	959	937
2	1108	1108	1108	1812	1812	1812	1910	1894	1850
4	1108	1108	1108	1812	1812	1812	3588	3588	3588
12	1108	1108	1108	1812	1812	1812	3588	3588	3588

From these three inter-transmission waiting times, the best results in terms of maximum number of aircraft in the corridor occur when the inter-transmission waiting time is 0.33 seconds. This is because the 0.33 second inter-transmission waiting time results in less time between transmissions which allows more aircraft to transmit in a given system refresh period. The largest maximum corridor capacity occurs over the 15 NMi separation at any of the three inter-transmission waiting times with at least four messages per transmission.

Corridor Loading Improvement

Having shown two methods for which the system of aircraft can transmit their data to ATC within the maximum allowed system refresh period, a traffic loading improvement measure will be considered.

The measure compares the maximum number of aircraft of the two transmission methods against the current peak traffic density. A single message per transmission ($b = 1$) represents an aircraft having to know only its own position, which is the worst case scenario for the system. Table 12 shows the percent differences between the peak traffic of 44 aircraft in the WATRS corridor and the number of aircraft calculated previously and shown in table 9 (for Method 1) and table 11 (for Method 2). Table 12 is based on equation 12, where N represents the number of aircraft that can be placed in the corridor at the specified separations for any of the three inter-transmission waiting times.

$$\%Increase = 100 * \frac{N - 44}{44} \quad (12)$$

TABLE 12.—ABSOLUTE PERCENT INCREASE IN MAXIMUM AIRCRAFT

Lat/Long Separation	b	Method 1			Method 2		
		0.33 sec	0.5 sec	1.0 sec	0.33 sec	0.5 sec	1.0 sec
50 NMi Separation	1	2418	2418	2414	2418	2418	2418
	2	2418	2418	2418	2418	2418	2418
	4	2418	2418	2418	2418	2418	2418
	12	2418	2418	2418	2418	2418	2418
30 NMi Separation	1	3084	2382	1405	4018	4018	4018
	2	4018	3573	2382	4018	4018	4018
	4	4018	4018	3573	4018	4018	4018
	12	4018	4018	4018	4018	4018	4018
15 NMi Separation	1	1061	805	448	2098	2080	2030
	2	1500	1236	805	4241	4205	4105
	4	1873	1664	1236	8055	8055	8055
	12	2218	2109	1864	8055	8055	8055

Table 12 shows the largest overall percentage increase in traffic over the current peak traffic density occurs with the following conditions:

- 15 NMi separation
- Method 2
- 4 or 12 messages per transmission
- Any of the three inter-transmission waiting times

If implementation allows only a single message per transmission, then the largest percentage increase in traffic density occurs with the following conditions:

- 30 NMi separation
- Method 2
- Any of the three inter-transmission waiting times

Conclusions and Future Work

This study is a high level, theoretical effort to understand and analyze oceanic aircraft traffic loading over the WATRS corridor. Numerous assumptions were made but care was taken to list them all. In a technical sense, given that the assumptions are correct, then the increases in traffic capacity shown in this report are also correct. The results generally show capacity increases when combining reduced aircraft separation requirements with ADS transmissions to ATC. Such capacity increases suggest that introducing ADS data over satellite communications links will accommodate potential traffic growth. It is strongly cautioned that incorporating procedural requirements could change the results.

This study established an analytical methodology to analyze this kind of scenario. Table 4 shows that based only on geometry, the WATRS corridor can support 1108 aircraft at a separation of 50 NMi. Note that 50 NMi is the current mandated oceanic separation, and is based on a lack of surveillance data. That being so, adding ADS transmissions through an AMSS are of no benefit for 50 NMi separation situations. However, ADS transmissions can be the enablers for reduced separations. Even though traffic growth as high as 1100 flights is anticipated, any increase in traffic that would be implemented through a separation reduction can not be accomplished without the benefits of an ADS/AMSS solution.

Future work in this area could include a comparison of other satellite systems with a consideration for more specific corridor loading limitations and predicted future growth. Analysis of newly defined oceanic requirements can be made as they arise. Also, this type of analysis over the WATRS corridor can be applied to other oceanic and remote regions, (i.e., Polar Corridor, African continent, Euro-Asian corridor), with similar additional comparisons done on those corridors as well.

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13. ABSTRACT (Maximum 200 words) Air traffic control (ATC) mandated, aircraft separations over the oceans impose a limitation on traffic capacity for a given corridor, given the projected traffic growth over the Western Atlantic Track Routing System (WATRS). The separations result from a lack of acceptable situational awareness over oceans where radar position updates are not available. This study considers the use of Automatic Dependent Surveillance (ADS) data transmitted over a commercial satellite communications system as an approach to provide ATC with the needed situational awareness and thusly allow for reduced aircraft separations. This study uses Federal Aviation Administration data from a single day for the WATRS corridor to analyze traffic loading to be used as a benchmark against which to compare several approaches for coordinating data transmissions from the aircraft to the satellites.				
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